FOUND
Analysis of fatigue and other cumulative ageing to extend lifetime

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FOUND focused mostly on structural integrity assessment techniques but experimental research on fatigue and residual stresses was also performed.

Work packages:
1. Remaining lifetime and LTO of components having defects
2. Susceptibility of BWR RPV internals to degradation mechanisms
3. Fatigue usage of primary circuit
4. Fatigue and crack growth caused by thermal loads
5. Development of RI-ISI methodologies
6. Dynamic loading of NPP piping systems
7. Residual stresses measurement techniques
FOUND 2015-2018

- Four year volume of the project: ~100 man-months
- >60 deliverables (research reports, conference papers, journal papers, theses)
- All deliverables can be found in the tinyurl-link on top of the slide and in the SAFIR extranet (password required)

https://tinyurl.com/yyyy9l4dw
WP1 – Remaining lifetime and LTO of components having defects

- The focus of this work package is in the methods required to evaluate the lifetime of components having defects.

- The research concentrated on:
  - The evaluation of the total safety factor in structural integrity assessment (appears to be impossible to quantify and depends on the case)
  - Uncertainties in loads due to thermal mixing was found to be governed by the mixing frequency and heat transfer coefficient
  - Evaluation of the J-integral with residual stresses some improvements over the Abaqus built-in routine were made
  - Comparison of allowable flaw size rules in ASME XI and BS7910 standards (the methods generally agree but differences exist in extreme cases)
WP2 - Dissertation on degradation of RPV internals

This work package provided an investigation on the susceptibility of BWR RPV and its internals and their supporting structures to various relevant degradation mechanisms during the LTO period.

A doctoral dissertation (Otso Cronvall) was prepared on the topic.

The results were used to support TVO’s application to renew the operating license of OL1-2 for 20 years further.
Fatigue is recognized as a major ageing mechanism in nuclear power plants and fatigue lives in water environments are shorter than in air.

Beyond the general notion of an existing environmental effect, a consensus is still lacking to reliably quantify it for stainless steels.

In design, a scalar Fen factor is used to quantify the reduction in lifetime due to the environment.

US NRC RG 1.207 and NUREG/CR-6909 address the issue.

In this WP, an effort to quantify the Fen factor for stainless steels was made and an updated Fen formulation was proposed.
WP 3 – Environmentally assisted fatigue in PWR water

Several strain-controlled low-cycle fatigue tests in PWR environment were performed using $\phi 8 \text{mm}$ 347 and 304L stainless steel specimens.

<table>
<thead>
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<th>Year</th>
<th>Material</th>
<th>FaBello rig</th>
<th>$\varepsilon_s$ [%]</th>
<th>Waveform</th>
<th>$\dot{\varepsilon}_1$ [s$^{-1}$]</th>
<th>$\dot{\varepsilon}_2$ [s$^{-1}$]</th>
<th>$\dot{\varepsilon}$ switch point</th>
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SIS transient
WP 3 – Environmentally assisted fatigue in PWR water

347

AISI 347
T=325 °C
Low DO water

Predicted $F_{en}$ from NUREG/CR-6909

- $F_{en}=10.99$
- $F_{en}=7.35$
- $F_{en}=9.17$

Defined from NUREG mean

- $F_{en}=7.35$

Difference between the current results and current design rules

304L

AISI 304L
T=325 °C
Low DO water

Predicted $F_{en}$ from NUREG/CR-6909

- $F_{en}=10.99$
- $F_{en}=7.35$
- $F_{en}=9.17$

Defined from NUREG mean

- $F_{en}=7.35$

Note $F_{en}$ prediction 6.12

Inside marker indicates reversed strain waveform
No inside marker indicates SIS transient

* based on PVP2017-66197

https://tinyurl.com/yyyy9l4dw deliverables D3.*
WP 3 – Environmentally assisted fatigue in PWR water

- New VTT approach to modelling EAF is based on
  - Plastic strain and strain rate instead of the total strain

- The model is based on:
  - Material specific mean curves
  - Temperature effects separately
  - Insensitive strain range based on elastic strain
  - Strain amplitude dependent

25/03/2019 VTT – beyond the obvious
WP4 Fatigue and crack growth caused by thermal loads

Spectrum method to generate load signals for high-cycle mixing loads

$P(f) = \frac{T_{RMS}^2 2\Gamma(\frac{6}{5})}{\sqrt{\pi \Gamma(\frac{3}{5}) f_{ref}}} \left[ 1 + \left( \frac{f}{f_{ref}} \right)^2 \right]^{-5/6}$

CSD Spectrum

Theoretical Spectrum

CFD Spectrum

Synthetic temperature signal

Stress and fatigue analysis

Temperature (°C)

Frequency (Hz)

Lifetime (days)
WP4 Fatigue and crack growth caused by thermal loads

Surface crack response to local periodic low-cycle thermal mixing loads
WP5 Development of RI-ISI methodologies

This work package developed methods required to assess the risk of failures in piping components.

The research topics included:

- Qualification of the VTT RI-ISI toolkit (± small differences to similar probabilistic codes)
- Effect of different POD functions on piping failure probabilities (± larger differences caused by other parameters than the POD function)
- Extension of VTT RI-ISI to LBB assessments (± still requires the accurate leak rate calculations for correct leak probabilities)
- Coupling of PRA and RI-ISI methods (± different failure consequence measured implemented in FinPSA to provide risk measures for RI-ISI assessment)
WP5 Development of RI-ISI methodologies

VTTBESIM RI-ISI approach

- A Monte-Carlo based probabilistic fracture mechanical tool to evaluate failure probabilities of flaws in piping.
- A key component is to consider initial flaw distributions and effects of periodic NDE inspections on the failure probabilities.
This work package was designed to provide tailored tools for more accurate NPP piping vibration analyses. The developments included:

- Methods to linearize non-linear supports (Can be linearized on a case-by-case basis but a generalized solution was not found)
- A simplified method to take into account the fatigue usage of decaying part of the vibration response (An analytical formula was found for a linear SN-curve, pointwise ASME BVPC fatigue curves require numerical integration)
- Load combination rules for improved accuracy and efficiency (Can result in 25% smaller load resultant and/or >90% computational savings)
- An ad-hoc fluid-structure-interaction tool to assess the piping stresses due to a water hammer event (FSI can increase the stresses if the piping response frequency coincides with the fluid excitation frequency)
WP7 Residual stresses and relaxation

Research on the residual stress measurement techniques and WRS measurements were done in this WP.

The resolution of the contour technique to measure WRS’s was significantly improved due to white light interferometry.
WP7 Residual stresses and relaxation

WRS measurement of TVO T-junctions 28 years in service:

Figure 9. The weld and various artifact shown with the measurement.
WP7 Residual stresses and relaxation

WRS measurements and welding simulation results of a modern Alloy 52 narrow-gap weld

Figure 3 Location of the EPR™ RPV Alloy 52 dissimilar metal welds (IRNS 2015 (modified), Wells et al. 2009).
These results and many more can be found via the link above.

The work continues in SAFIR2022 project FEVAS